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TRANSPORT AIRPLANE FLIGHT DECK DEVELOPMENT SURVEY AND ANALYSIS: REPORT AND RECOMMENDATIONS

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16. Abstract
This document reports results of a survey and analysis of current research and development work in the U.S.A. related to improving transport airplane flight deck equipment and aircrew performance. This survey and analysis was performed for the NASA Langley Research Center's Terminal Configured Vehicle (TCV) program, which was established to study, test, and evaluate concepts for more efficient and more acceptable terminal-area transport operations. Research and development related to flight deck advancement in general, as well as that concerned directly with terminal-area operations, is described and discussed. Specific recommendations are made for future TCV program work in flight deck development, based on survey results.

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1.0 SUMMARY

The NASA Langley Research Center Terminal Configured Vehicle (TCV) program has been established to develop, evaluate, and demonstrate systems and procedures for more efficient and acceptable transport aircraft operations approaching and within terminal areas.

One task of the TCV program was to conduct a survey and analysis of flight deck related research and development being conducted elsewhere in the U.S. The object of this task was to establish a base and context for future TCV program flight deck research aimed at optimizing the aircrew-aircraft interface.

A summary and discussion of survey data and its analysis with respect to TCV goals and objectives is presented herein, followed by recommendations for program action. Specific recommendations are made for:

- Documentation of activity
- Control/display concept development
- Advanced control/display system performance assessment
- Visual approach monitor and head-up display evaluation
- Tactile display evaluation
- Cockpit displayed traffic information analysis and test
- Keyboard reconfiguration
- Workload evaluation and validation
- Stereo display evaluation
- Imaging sensor evaluation

2.0 INTRODUCTION

The broad objectives of the Terminal Configured Vehicle (TCV) program are to provide improvements in airborne systems (avionics and air vehicle) and in operational flight procedures for:

- Reducing weather minima
- Reducing noise
- Saving fuel
- Increasing air traffic controller productivity
- Increasing airport and airway capacity
- Improving approach and landing safety

The program involves analyses, simulation, and flight studies using a modified Boeing 737 (B-737) airplane. The TCV B-737 has two operational flight decks, one forward (FFD) and one aft (AFD), as shown in figure 1. The AFD, shown in detail in figure 2, is equipped with highly flexible display and control equipment. During research operations, the airplane is flown from the AFD. Safety pilots in the FFD monitor all maneuvers and can take control at any time.

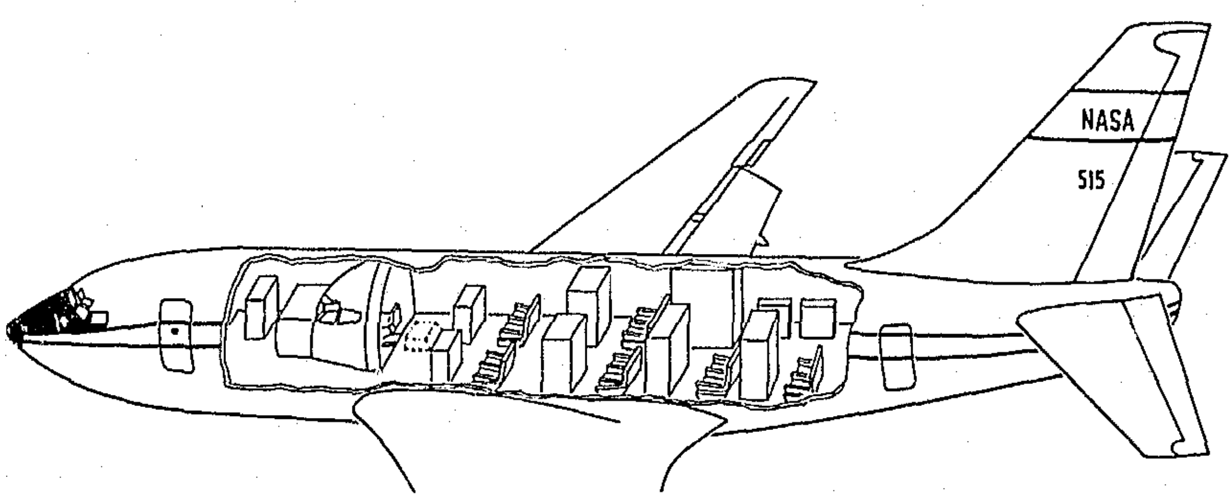

Figure 1.—TCV B-737 General Arrangement

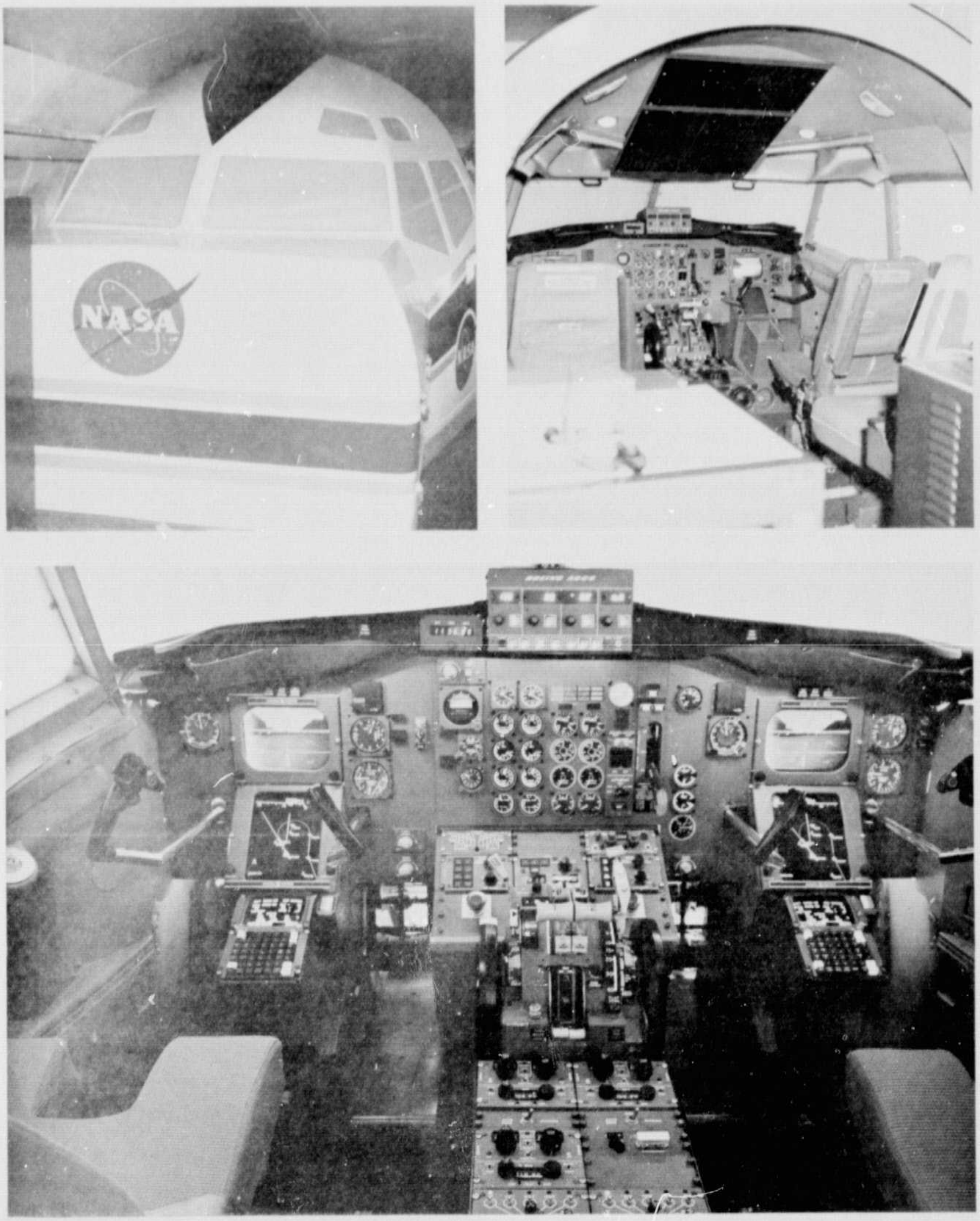

Figure 2.—Aft Flight Deck

The objective of the program task reported herein was to establish a data base of flight deck related research and development and, based on this information, to make recommendations for future program research on controls, displays, and aircrew procedures. The task was accomplished by means of a comprehensive survey of other organizations engaged in appropriate R&D, and a concurrent analysis of survey data with respect to the objectives and capabilities of the TCV program.

The survey was initiated by making telephone contact with individuals working in areas such as cockpit design, control/display development, and aviation human factors research. Some of these individuals were known at the outset, and others were suggested by persons contacted as the survey progressed. Approximately 120 individuals were contacted, representing 10 universities, 20 government/military offices, and 40 private companies. Organizations and individuals are listed in the activity and trip reports on file in the TCV program office.

The approach to each contact was to briefly describe the TCV program, if necessary, explain the purpose of the survey, and then request information concerning relevant research and development activities in that person's organization. Approximately half of the persons contacted had heard of TCV, but most requested a description of the program and its current status. Fifteen program brochures were mailed or otherwise delivered to those who requested them. Arrangements were made for personal visits to those organizations whose activities appeared most relevant to flight deck development. Nine survey trips were made in which thirteen organizations were reviewed, and four symposia were attended.

3.0 ABBREVIATIONS

ADEDS	Advanced Electronic Display System
AFAL	Air Force Avionics Laboratory
AFB	Air Force Base
AFD	Aft Flight Deck
AFFDL	Air Force Flight Dynamics Laborato
AGCS	Automatic Guidance and Control System
AIDS	Advanced Integrated Display System
AIMIS	Advanced Integrated Modular Instrumentation System
AMRL	Aerospace Medical Research Laboratory
AOA	Angle of Attack
ASM	Advanced Systems Monitor
ASW	Anti-Submarine Warfare
ATC	Air Traffic Control
AWACS	Airborne Warning And Control System
CDTI	Cockpit Displayed Traffic Information
cm	Centimeters
CRT	Cathode Ray Tube
CWS	Control Wheel Steering
DAIS	Digital Avionics Information System
DH	Decision Height
DLC	Direct Lift Control
EADI	Electronic Attitude Director Indicator
EHSI	Electronic Horizontal Situation Indicator

EKG	Electrocardiogram
EL	Electroluminescence
FAA	Federal Aviation Administration
FFD	Forward Flight Deck
FLIR	Forward-Looking Infrared
FPA	Flight Path Angle
FRD	Flight Research Division
GD	Gas Discharge
HSD	Horizontal Situation Display
HUD	Head-Up Display
IFR	Instrument Flight Rules
ILM	Independent Landing Monitor
LAS	Landing Assessment System
LCD	Liquid Crystal Display
LED	Light-Emitting Diode
LEF	Light-Emitting Film
LLLTV	Low Light Level Television
mA	Milliamperes
MDA	Minimum Descent Altitude
MIT	Massachusetts Institute of Technology
MLS	Microwave Landing System
NAS	Naval Air Station
NASA	National Aeronautics and Space Administration
NCDU	Navigation Control and Display Unit
ONR	Office of Naval Research

OSU	Ohio State University
PAFAM	Performance and Failure Assessment Monitor
PLZT	Pb-based Lanthanum-doped Zirconate Titanate
R&D	Research and Development
RVR	Runway Visual Range
SAE	Society of Automotive Engineers
TCV	Terminal Configured Vehicle
TCV B-737	TCV Boeing Model 737-100 Aircraft, NASA Designation 515
TLA-2	Time-Line Analysis Crew Workload Evaluation Computer Program, 2nd version
TSC	Transportation Systems Center
TV	Television
UG3RD ATC	Upgraded Third-Generation Air Traffic Control
V	Volts
VAM	Visual Approach Monitor
VFR	Visual Flight Rules
VPI	Virginia Polytechnic Institute
VRAS	Voice Recognition and Synthesis
V/STOL	Vertical/Short Takeoff and Landing

4.0 SURVEY AND ANALYSIS

4.1 GENERAL

Survey data was found to fall into two major categories: (1) that which affects or is immediately concerned with terminal area operations, and (2) that which is applicable to flight deck development in general. Accordingly, the following discussion is divided into these two categories.

In general, the survey found relatively little research and development (R&D) activity aimed specifically at transport flight deck development. The scope and complexity of military and commercial transport operations has created formidable economic, technological, and regulatory barriers to the introduction of new controls, displays, and flight procedures for transport aircraft. These barriers are interrelated and combine to make economic incentive for independent R&D uncertain at best and long-range in any case. Transport flight deck R&D is thus largely confined to programs either funded or performed by government agencies and to independent, long-range work by the major transport airplane manufacturers.

Other general aspects of flight deck related R&D which emerged in the course of the survey are:

1. Most genuine human factors research activity addresses very specific, very fundamental aspects of general human abilities and behavior. Untrained subjects and relatively simple tasks are necessarily used in this work. Extrapolation and application of such research results to the complex problems TCV must address is both difficult and risky.

2. Most developmental activity is aimed at eventual production of a specific end item for a military or industrial market, and understandably so. In the future time frame which TCV addresses, the market is predominantly military and most developmental work is aimed at combat aircraft applications. Commercial aircraft flight deck developmental work will more likely and perhaps more appropriately be guided by, rather than provide guidance to, the TCV program.

3. Because transport flight deck R&D is fragmented and oriented to immediate problems, the field lacks a focal point and a common or unifying long-range objective. The TCV program has the potential to become the focal point and to provide long-range objectives for the entire field.

4. Despite an abundance of conferences, symposia, and technical literature, effective communication among those engaged in or having resources for flight deck R&D remains a problem. Informal technical interchange is evidently uncommon. A surprising amount of provincialism exists in many research organizations, accompanied by apparent lack of interest in "other" R&D activity.

4.2 TERMINAL AREA OPERATIONS

4.2.1 GENERAL

The central issue of future terminal area operations, and that which TCV can most productively address, is the problem of providing the aircrew sufficient control and display capability to either guide or monitor the airplane's progress along a three- or four-dimensional curved or segmented path to a safe landing. Moreover, the crew must be capable of performing this task regardless of weather and visibility conditions. Because the problem of low visibility currently exists for straight-in approaches, it has received considerably more developmental attention than potential future problems arising from routine use and performance of complex approach paths.

In this section, a relatively short discussion of "piloting" is followed by a longer discussion of "low-visibility landing", which includes data from work on landing assessment systems, or independent landing monitors, and head-up displays. Description of a tactile display device, a novel form of "head-up display," is also included. Finally, a possible means of aiding coordination with other air traffic is discussed. This concluding discussion is limited to the concept of a cockpit display of traffic information (CDTI). No attempt is made to address the counterpart problem of air traffic control in general.

4.2.2 PILOTING

The task of piloting an airplane through the maneuvers required in terminal-area operations is one which receives almost continuous attention, but seems not to benefit appreciably from this attention in terms of improved instrumentation and controls. Perhaps the last significant improvement in primary flight instrumentation for transport aircraft was the flight director. The operational improvement in safety which has occurred in the last decade is largely attributable to new or improved ground-based landing aids. Some additional improvement is also due to better pilot training and accumulated pilot experience.

The improvement due to new and improved ground aids underscores the fact that the pilot's greatest need in the cockpit is a means of quickly and continuously ascertaining his position and progress in the three-dimensional environment. The steady improvement due to training and experience indicates that terminal-area maneuvers as currently performed are neither quickly nor easily learned. Such maneuvers are particularly difficult under the not infrequent adverse conditions in which they must be routinely performed.

Terminal-area maneuvering will become even more complex in future operations involving curved, decelerating, and segmented approaches. Future time navigation requirements and closer lateral and longitudinal spacing of arriving and departing airplanes will require not only that the pilot know precisely where he is and where he is going at any given moment, but also that he be able to very precisely control his progress.

The Air Force Flight Dynamics Laboratory (AFFDL) recently completed a simulation study and flight test demonstration, in a T-39, of microwave landing system (MLS) guided curved and segmented approaches using conventional instrumentation. Conclusions stated in the published flight test report (ref. 1) are not particularly revealing, but comments of the pilots who flew the demonstration flights are included in the report. Pilot comments center principally around the topic of orientation and the need for improved position/situation information in the more complex MLS profiles.

The AFFDL program evidently generated some criticism of the MLS as lacking in guidance information. A subsequent memorandum (ref. 2) points out that displays for terminal-area navigation and precision path following are inadequate for *all* landing systems when curved and segmented approaches are flown. Paraphrasing the memo, it was the implementation of close-in instrument approaches, rather than the implementation of MLS, which identified the inadequacy of terminal-area navigation displays in use today. This difficulty was foreseen by an earlier Boeing/AFFDL study of control/display testing requirements for MLS operations (ref. 3). This study provided a basis for subsequent Air Force MLS evaluation work using a T-39 airplane.

The AFFDL MLS memorandum refers to TCV, and recommends Air Force evaluation of a projected path vector on an electronic attitude direction indicator (EADI) for both horizontal and vertical paths. Although the study showed that curved and segmented approaches can be flown using MLS guidance and conventional displays, it revealed that such approaches cannot be flown accurately without improved instrumentation. It is reasonable to further conclude that safety considerations will preclude use of such approaches, whether manually or automatically controlled, in daily commercial operations unless improved position/situation displays and path controls are developed and proved effective.

Development of such new or improved displays is well within current technology. The objective of such development should be to provide the pilot an integrated, easily interpreted representation of his position and progress, not only in the horizontal and vertical dimensions, but also with respect to a possible speed or time schedule. The most promising means of achieving this objective appears to lie in the flexibility of electronic displays for dynamic presentation of information, and the growing capability and availability of digital processing equipment to perform much of the information integration and interpretation which the pilot now must perform. If the pilot can be relieved of duties as a data processor, he can perform more efficiently as a decision maker and system manager. To complement this advantage, system management functions, such as subsystem monitoring and checklist operations, can also be assigned to the processor, thus permitting the pilot to devote more time and attention to primary control functions.

Many such development efforts are at present underway in all of the R&D arenas: military, commercial, and academic. Most of these efforts are basically similar in that nearly all the display concepts focus upon one or more electronic indicators: a pictorial horizontal situation display, a vertical guidance display oriented to flight path angle/velocity vector–either or both displays having some kind of predictive capability–and some type of systems monitoring concept. All have been somehow simulated, tested, or evaluated, and work proceeds on any given concept based on favorable results from whatever was done.

What is lacking in this area, and what TCV is uniquely capable of providing, are both (1) a quantitative, comparative assessment of the incremental gain in operational system performance that could be provided by any particular concept, and (2) identification of specific man-machine interaction problems which occur in the real-world operational context.

4.2.3 LOW VISIBILITY LANDING

The problem of low-visibility landing is difficult to identify in tangible terms. Automatic landings in Category IIIA conditions are now permitted by British and European airlines, and U.S. carrier-based Navy aircraft land automatically in similar conditions. A French Air Force airplane has made 30 to 40 landings in less than 100 ft runway visual range (RVR) using a head-up display (ref. 4), and a U.S. Air Force T-39 has been landed repeatedly in the same conditions using little more than expanded-scale conventional instrumentation (ref. 5). Jimmy Doolittle took off, flew 15 miles, and successfully landed, using instruments only, in 1929*. So, the problem is not can it be done or how to do it, but rather how to provide both sufficient and sufficiently reliable information and control capability so that low-visibility landings may be made confidently and routinely, either in automatic or under manual control.

An important aspect of low-visibility landing is that of subsequent turnoff and taxi. Automatic turnoff, to clear the runway, is conceivably possible via some appropriate sensing, processing, and control system, but automatic turnoff in very low visibility is likely to be as controversial to U.S. airlines as are automatic landings. Automatic taxi to the terminal is difficult to imagine as a real requirement in the foreseeable future. Nonetheless, if the research goal is to achieve zero-visibility landing capability, the problem of getting the airplane from the runway to the terminal must be considered. (A concomitant problem is that of enabling ground support vehicles, such as fire trucks, to operate in zero-zero conditions.)

A possible solution to the low-visibility landing problem is to provide the pilot a display, with associated sensing and processing equipment, which will give him sufficient information to land the airplane confidently without need for outside vision. What information to display and how to display it for this purpose are questions nearly as old as aviation itself, and as yet not satisfactorily answered. Even given such a display system, the pilot might require assurance from some other source that the system was operating properly.

A similar requirement for pilot assurance was anticipated early in the development of automatic landing systems. From this now questionable requirement came the idea of an independent landing monitor (ILM), or more generally, a landing assessment system (LAS). The ILM concept consists of a display driven either by airborne sensing and processing components independent of the autoland system, by ground-based transmitters, or by a combination, such as airborne sensors and ground-based signal sources. The important feature is that the ILM presents the aircraft's situation independently; its information should be derived from sources other than the airplane's primary navigation or guidance system, and it should not depend upon ground-based

*New York Times, September 25, 1929. Headlined "FOG PERIL OVERCOME". Story on Page 1 continued on Page 7.

inputs to those systems. As usually defined, an ILM need not provide manual takeover capability for anything beyond aborting the approach. By contrast, a LAS is usually defined as a system which permits manual execution of approach and landing. To avoid misunderstanding, the generic term "landing monitor" is used in the following except where a more precise term is needed.

Most of the R&D relevant to "head-down" landing displays has been aimed at a landing monitor application. At least two such systems have been fully developed for commercial operations, one for the L-1011, the other for the DC-10. Neither is in active use in the U.S. at present.

For discussion purposes, landing monitor concepts may be divided into three general categories:

- Go - no go indication
- Dynamic, symbolic display
- Imaging sensor display

Go-No Go

This, the simplest concept, assumes an on-board system which continuously checks the health and operation of the autoland system and the quality of guidance signal being received. This approach, in itself, does not provide a manual takeover capability except to abort and divert. Neither does it provide turnoff and taxi guidance.

Dynamic Symbology

A second approach is to generate symbology, usually an artificial representation of the external environment, showing the airplane's present relative position and predicted progress. The performance and failure assessment monitor (PAFAM) is a relatively simple symbolic landing monitor (ref. 6) developed by Honeywell for McDonnell-Douglas and now standard equipment on new DC-10's. However, most U.S. airline DC-10 customers have either disconnected or removed the units. The reason given by one airline for removing their PAFAM's is that the unit does not, in their analysis, provide sufficient additional system capability to justify spares and maintenance costs. This explanation does not fault the display itself; its intended function is that of an autoland monitor, and autoland is at present available at relatively few airports.

National Airlines has operated PAFAM in an optional manual LAND mode during Category II operations, and the display is active in their training simulator. Their pilots like the display and desire it active in the airplanes.* Because PAFAM has a manual mode, and because the availability of autoland will continue to increase, evaluation of a PAFAM on the TCV B-737 might provide valuable information relevant to both TCV program goals and near-future airline operations.

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*National recently deactivated their PAFAM's for reasons not related to the PAFAM itself.

A more sophisticated symbolic landing display is an EADI landing format developed at Langley Research Center and tested in both the TCV simulator and airplane. The format features a runway symbol having perspective in both range and azimuth, velocity vector, and other symbology. All symbology overlays and registers with the actual runway as seen by forward-looking TV, when visibility permits. Simulator tests of the format (ref. 7) showed improved pilot performance in achieving alinement with the runway. Flight tests in the TCV B-737 are currently in progress.

Earlier tests at Boeing of a perspective runway landing monitor concept showed that (1) the runway perspective alone was clearly insufficient, and (2) although performance improved markedly with the addition of symbology, pilots were never able to make consistently accurate judgements of approach "quality" at a decision height of 100 ft (ref. 8). Follow-on flight tests of the concept (ref. 9) showed an even greater variability in performance due to signal interference not present in the simulation. Obviously, pilot acceptance of a symbolic display would depend upon the source and reliability of the signals and equipment used to drive the display, as well as the amount of information available from the symbology.

A symbolic display might also be used for turnoff and taxi, given an external guidance system on the taxiways, but the idea seems impractical. Of the three general approaches to a landing monitor, the symbolic display is the only one appropriate for evaluation on the TCV B-737 because it can be tested in good weather and without intentionally disabling the guidance system to achieve unsatisfactory indications.

Imaging Sensor Display

The third and probably most expensive landing monitor concept is that of providing imaging sensors and a sensor display on the airplane to show the pilot what is on the ground. Radar and forward-looking infrared (FLIR) are the two most likely sensors for such a system, and each has the disadvantage of being attenuated by different types of fog and precipitation, thus limiting their overall utility. Both offer good resolution under most conditions. FLIR is attenuated most by heavy, wet fog, and radar by heavy rain.

An ILM that used a Texas Instruments Ka-band radar was developed for the L-1011 but was not purchased by any L-1011 customer. An improved version of this ILM has been flight tested by AFFDL in a KC-135. Results of this evaluation, not yet published, indicate that the radar is an effective sensor for all kinds of runways in nearly all kinds of weather.

As expected, test results show that heavy rain attenuates the signal; however, an unanticipated and possibly more serious effect is that standing water evidently causes a loss in discriminability. The ILM has a ±15-deg scan, a 4-mile viewing range, and approximately 200 ft short-range limitation. Resolution is said to be sufficient for taxiing, but the sector size scanned would have to be increased. Trucks and other metal objects intentionally placed on runways appeared on the radar before the runway did. People on the ground and even birds could be seen on the display.

Texas Instruments has considered combining a Ka-band radar with airline weather radar, but this idea is not at present being pursued.

A FLIR system developed by Hughes for the Air Force was later tested by Hughes and Boeing, Wichita, as a possible Boeing 747 ILM candidate (ref. 10). Ground tests showed that the system provided two to ten times the visual range of the eye in various types of haze and fog (ref. 11). A second test of the system was planned for this year, but has been indefinitely postponed.

Experience with the B-52 indicates that the FLIR could provide guidance for turnoff and taxi, but it is unlikely that such a display could provide enough information for confident landing. This characteristic is not unique to FLIR, however. Two-dimensional, TV-type displays in general have up to now been unsatisfactory as primary landing displays (refs. 8 and 12). Landings can and have been made using a TV display (refs. 13 and 14), but the technique is still experimental. In any case, an imaging sensor system is not amenable to testing on the TCV B-737. Such testing would require making approaches in actual lower-than-minimum visibility in which the safety factor provided by the front cockpit would be lost.

Two other possibilities for imaging sensor display development, both of which would add to system cost, are (1) a multisensor system with integrated sensor information, and (2) three-dimensional display. Westinghouse has tested a combined low-light-level television (LLLTV) and FLIR system in which the individual sensor signals are processed so that they are complementary, rather than superimposed (ref. 15.) To further enhance the image quality, artificial color was added in some tests as a means of edge sharpening. For target detection and recognition, the color-enhanced display proved better than either of the sensors singly, with or without color, or combined in monochrome.

Both RCA and Honeywell have developed three-dimensional TV viewing systems using electrically controlled PLZT optical filters installed in special lightweight goggles similar to sunglasses. The polarized lenses are electro-optically rotated by the PLZT at the TV field rate to alternately block the view of each eye, thus permitting the viewer to see two images as one stereo image. The advantages of the PLZT approach over other methods are that (1) it can be used with either color or monochrome displays, and (2) the viewer can look away from the display for other purposes without suffering distorted vision. The lenses do attenuate vision, however, as do dark sunglasses (refs. 16 and 17).

It would be interesting to discover whether or not a three-dimensional image would increase pilot confidence in landing using a TV display. Factors such as inter-camera spacing and focal points would have to be worked out first. Resolution of these factors and the actual evaluation are almost necessarily flight tests, because the technique would be difficult to simulate realistically. The application could be to either a symbolic or a sensor display, but it seems more appropriate for an actual picture.

Several efforts to develop a head-down landing display as such, not a landing monitor, were found in the survey. The first is the EADI perspective runway format discussed earlier. In addition, a path-in-the-sky format for the EADI is under experimental development at Langley Research Center. This display is just now being readied for simulator evaluation.

A head-down, path-in-the-sky display for carrier landing was successfully demonstrated in simulation at Pacific Missile Test Center (ref. 18). The display showed a flight path corridor and a carrier symbol. The simulation was of an F-4 airplane, but did not include carrier dynamics.

Work on a predictive symbolic concept is proceeding at the Aviation Research Laboratory, University of Illinois. (One such format is shown in fig. 3, taken from ref. 12.) Figure 3 shows the airplane banked to the right, low and to the left of the glideslope. The successi‘ .ly smaller airplane symbols show that the pilot has made the proper control input to pul! up and roll left to bring the airplane to the desired touchdown point. The concept has not yet been tested in simulation.

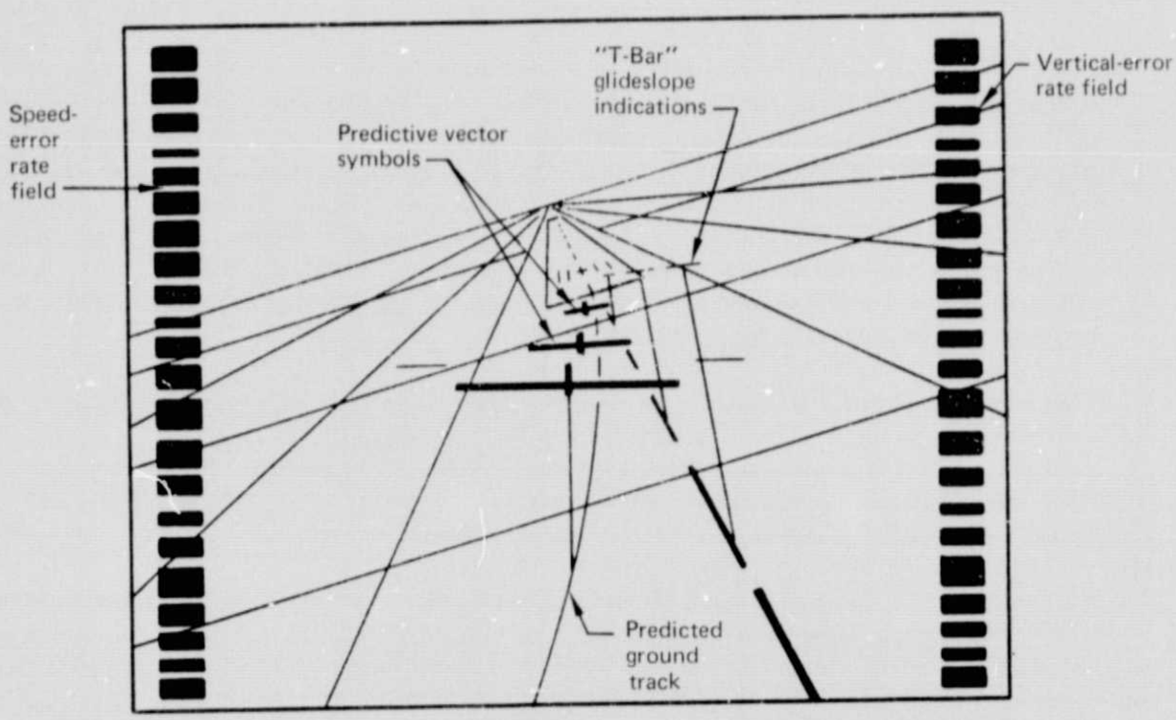


Figure 3.—Computer-Generated Contact Analog Display With Fast-Time Predictive Flight Path Projection

4.2.4 HEAD-UP DISPLAYS

The head-up display (HUD) is now the primary flight display on new military combat aircraft, i.e., the F-14, -15, -16, and -18. Because these aircraft are new, and because preceding head-up displays, such as that on the A-7, were primarily for weapon delivery, little or no evaluation has been recorded for these HUD's as low-visibility landing displays. Operational information of this nature may be expected in the future, however, as these new airplanes are forced to fly into bad weather.

Theoretically, the HUD permits the pilot to monitor essential instruments and to look for the ground without having to either move his head up and down or refocus his eyes. The information on the HUD is collimated and thus "focused at infinity." There is some question whether or not collimation is necessary, and this question is now being experimentally evaluated at Pensacola Naval Air Station. In the F-15, HUD collimation forces the pilot to move his head slightly from side to side in order to alternately view airspeed and altitude scales on either side of the display. In addition, the pilot must look up, rather than down, to check the heading scale at the top of the HUD. On the F-14, the HUD and canopy configuration causes undesirable reflections, particularly at night. The display is not currently used for landing, because pilots position themselves above the design eye point prior to approach, and in this position cannot see the display.

The principal argument for the HUD as a low-visibility landing aid is that it permits a how-goes-it approach to decision height rather than forcing the pilot to look up and make a snap decision at decision height/minimum descent altitude (DH/MDA). This argument is not entirely applicable to commercial aircraft, where the usual procedure is for one pilot to remain on instruments while the other alternately checks instruments and looks out. While this procedure is basically sound, review of short-landing accidents and premature ground strikes reveals that, when visibility is borderline or spotty, both pilots sometimes yield to the temptation to look for the runway, and thereby let the airplane get away from them (refs. 19 and 20).

There are evidently a number of subtle aspects to use of head-up displays. A characteristic pattern in the military is for pilots to dislike the HUD initially and use it very little. As the display is used, however, they become advocates. This transition is often described as "unconscious," and a common remark is something like "I didn't realize how much I depended on the HUD until it failed just as I was . . .".

An evaluation of the Sundstrand Visual Approach Monitor (VAM), a relatively austere HUD, was performed by AFFDL with a C-5 airplane (ref. 21). The evaluation concluded that pilots must be trained to use the VAM, and revealed that piloting technique varies depending on whether the display is used as a monitor or as a director; an apparently self-evident statement, but intended to describe a subtle effect. The VAM evaluation also concluded that the display was not useful in low visibility because of difficulty in transitioning from the display to the real world after breakout. Its greatest utility, according to the report, was in cases where the pilot could see the ground but had no good horizon reference. In defense of the VAM, it must be noted that (1) the display was an early model, (2) the Air Force significantly modified the display, and (3) installation problems on the C-5 affected the evaluation negatively.

Other general arguments against the HUD include limited field of view and a cluttered format which can actually obscure visual cues rather than assist in acquiring them. Less tangible objections are (1) the display can be very compelling and may "fascinate" the pilot, and (2) when the visual field is homogeneous, the eyes involuntarily focus at about arm's length; thus, the pilot really can't look for the ground at all until it comes into view, at which time he must refocus his eyes anyway. On the other hand, if the visual field is homogeneous, focusing on collimated HUD information may be the only way to enable the pilot to see through the fog.

The most recent published test of a HUD was for V/STOL landing in the CL-84 airplane. Results are said to be ambiguous, and at any rate would be difficult to extrapolate to airline operations. The current Pensacola tests are not intended to reveal more than the effect of collimation. Hughes' "diffraction optics" HUD (ref. 22) will be flight tested in 15 to 18 months, but it is not known whether these tests will include low-visibility approach and landing.

It appears unlikely that any compelling evidence or rationale either for or against a commercial transport HUD will soon be forthcoming until it has undergone a well-designed evaluation program. Such an evaluation would require closed-loop visual simulation in which differing visibility conditions could be realistically represented, and different approaches could be flown. As a first step toward the evaluation, the requirements for such a simulation study should be identified, and the capability of LRC simulators should be evaluated with respect to these requirements.

The utility of installing a HUD on the TCV B-737 for actual low-visibility evaluation appears doubtful, though a HUD vendor has indicated possible support in providing hardware. If installed in the forward flight deck, only VFR evaluations could be made. If installed in the aft flight deck, only zero-zero conditions–not a realistic HUD role–could be studied. An evaluation of the HUD as an aid in genuine low-visibility conditions thus could not be made within the scope of the current TCV program.

Perhaps the most profitable HUD-related endeavor for TCV would be evaluation of the VAM. The forward flight deck is configured to accept the VAM, and the manufacturer, Sunstrand Corp., has indicated willingness to provide both hardware and technical support for a VAM evaluation. Additional support may be available from AFFDL where there is interest in use of the VAM for two-segment approaches. Although the evaluation would not be immediately relevant to the low-visibility landing problem, experience gained in using the VAM would be valuable toward identifying requirements for a full HUD evaluation program.

4.2.5 TACTILE DISPLAY

A tactile display which can be driven by any appropriate signal has been developed at Ohio State University (OSU, refs. 23 and 24). The device is a servo-driven metal cylinder which, as currently configured, fits into the left handgrip of the cockpit control yoke. At its null position, the ends of the cylinder are flush with the contour of the grip. The cylinder moves fore and aft within the grip to indicate or command an increase or decrease in the driving variable, angle-of-attack (AOA). The display has been shown to significantly reduce the time required to teach student pilots to land.

By its nature, the device is best suited to command information or error presentation where a specific and desired null state can be defined. Though it is currently used as an AOA command, it could be implemented to command any single-dimensional parameter such as airspeed, flight path angle (FPA), or even direct lift control (DLC). The potential advantage of the device for experienced pilots is that the display can provide a continuous qualitative indication in a relatively unused sensory channel, thus unburdening the visual channel by at least one parameter. Its role and utility for experienced pilots has not been assessed at OSU. A two-axis device is being designed, but initial evaluation of the existing single-axis device would be simpler and perhaps more revealing.

4.2.6 CDTI

The cockpit-displayed traffic information (CDTI) concept consists of an electronic horizontal situation display (EHSI) in the cockpit on which other air traffic can be displayed to the aircrew. The basic premise, based in part on results of simulation studies at the Massachusetts Institute of Technology (MIT) and the NASA-Ames, in conjunction with Tufts University, is that the pilot can contribute significantly to the efficiency of certain airline operations, particularly terminal area operations, if he has such a display. The concept is many-faceted and very complex, giving rise to questions involving virtually all aspects of current and future terminal area operations, not the least of which is legal liability for accidents.

The Boeing Company, under direction of the Transportation Systems Center (TSC) and the Federal Aviation Administration (FAA), and sponsored by the TCV program, has recently completed a CDTI role feasibility study (ref. 25), in which potential benefits were analyzed and a test and evaluation program outlined. The fundamental question concerning CDTI is whether it might be more of a liability than an asset to safe and efficient operations. It is feared that pilots might find the display fascinating, and neglect other instruments; or initiate frequent and usually needless communications with ATC to question the intent of other airplanes; or disrupt a complicated, but carefully coordinated, flow of traffic by taking independent action based on misinterpretation of the situation.

Because of these potential problems, one general recommendation of the Boeing study is that "future simulation and testing be done in a realistic traffic situation and ATC environment to preclude misleading conclusions that simpler testing can promote." In individual role-test recommendations, it is further stated that both hazardous and safe but apparently hazardous situations must be simulated. Because the concept is potentially dangerous, evaluation of its weaknesses, not just its strengths, should be the object of future testing.

4.3 GENERAL FLIGHT DECK DEVELOPMENT

General flight deck development comprises controls and displays for secondary tasks, such as subsystems monitoring and navigation or communications input and output. These tasks interact both directly and indirectly with primary flight tasks, directly by requiring periodic, flight-related aircrew actions, and indirectly by imposing general housekeeping and caretaking duties performed on a time-available basis. As discussed in section 4.2.2, a major objective of primary control/display development must be to unburden the aircrew and thus provide additional time and opportunity for systems management. Similarly, a major goal of general flight deck development must be to provide the aircrew the greatest possible facility for understanding and controlling the overall situation of their airborne system.

As in piloting, the greatest potential for general flight deck development appears to lie in the application of onboard processing equipment to achieve an integrated, system-oriented design. Integration of subsystem control and display functions at the processor level is a difficult concept, however, because (1) there are a large number and wide variety of individual parameters, (2) each parameter has significance of its own, and (3) the significance to the system of any particular parameter varies as an often complex function of other parameters. Because of these properties, subsystem control and display development tends to proceed piecewise on a subsystem level, and the interpretation and integration of subsystem parameters with respect to the total system is left to the aircrew.

Recent and current developmental efforts, focused upon centralizing subsystem control and display provisions on a single time-shared panel, are more accurately described as consolidation, rather than integration. Given a digital avionics system, however, a further step toward integration is possible in that single data inputs or requests can be made to the central processor, which then either supplies or retrieves the data to or from all relevant subsystems. Barometric pressure, for example, must at present be set and verified in no less than seven separate locations in some wide body transport cockpits, a result primarily of postdesign requirements for add-on and backup systems.

How to achieve continuous and accurate interpretation of subsystem parameters by a processor, and the most effective means of subsystem information presentation, are areas which require work. True integration of subsystem functions with respect to the aircrew interface is meaningful perhaps only for accomplishing or verifying changes in system configuration, i.e., system mode change via a single switch operation. This concept basically implies automatic performance and verification of checklist functions.

4.3.1 CAUTION AND WARNING SYSTEM

Boeing is currently conducting a study for the FAA of cockpit caution and warning systems. Related efforts are also being pursued by the NASA-Ames and by the Society of Automotive Engineers (SAE) S-7 Committee on cockpit displays and controls. McDonnell-Douglas and Lockheed are scheduled to be involved in forthcoming program phases involving human factors tests of alerting system concepts. The ultimate objective of the program is to provide design standards for cockpit alerting systems.

A concurrent internal effort at Boeing is a study of time and criticality factors associated with various types and combinations of subsystem failures. The intent of this study is to develop an underlying theory applicable to the design of any caution and warning system. Caution and warning concepts are not attractive candidates for airborne test and evaluation due to possible conflict or confusion with actual, instead of simulated, problems. New caution and warning concepts may be candidates for implementation, however, when or if an extensive TCV cockpit reconfiguration is made.

4.3.2 SYSTEMS MONITOR

The Advanced Systems Monitor (ASM), developed by Boeing in cooperation with Teledyne, will be flight tested during the coming year on Boeing's 720B airplane. Similar systems are under development for the Navy Advanced Integrated Display System (AIDS) and the Air Force Digital Avionics Information System (DAIS) programs. Test and operational data concerning display formats and system functional requirements should be forthcoming from all three sources.

It is inevitable that an electronic display of systems status and an associated monitoring subsystem will come to commercial aircraft, for any number of interrelated reasons, such as:

1. Continuous dedicated display of systems parameters is not necessary, and in some cases is undesirable.

2. Continuous automatic monitoring and selective automatic display of out-of-tolerance parameters in a single, fixed location offers obvious advantages for recognition of and reaction to system faults.

3. With a digital avionics system, such as AIDS and DAIS, conventional display of systems data is impractical.

4. Even without a digital avionics system, electronic displays can be significantly more economical than conventional indicators (ref. 26).

Integration of the systems monitor with the cockpit caution and warning system is also an obvious eventuality, but such integration will probably proceed slowly. The integrated system will require development and implementation of digital sensors and actuators, and will be initially expensive to install. For these reasons, a systems monitor is not recommended for flight test on 515, but like the caution and warning system, should be a primary consideration in the event of cockpit reconfiguration. Simulator testing of such a system would be more appropriate and certainly more economical at this time. The automatic checklist function is immediately applicable, however, and this function might be progressively implemented on the airplane, one parameter at a time.

4.3.3 KEYBOARD

The primary "keyboard" in commercial airplane cockpits is at present, and probably will be for some time to come, the navigation system control head. The more flexible and capable the navigation system is, the more instructions it requires, and the more complicated the control head becomes. The language of navigation comprises nearly all the letters of the alphabet, all the numbers, some kind of punctuation, and anywhere from two or three to a dozen or more modes or functional alternatives. Keyboard complexity is only a manifestation of a more basic problem, however, which is that the computer is designed for navigation and not for man-machine communication. But, in this case, identifying the problem does not appear to help much in solving it. In attempting to solve the problem there is even danger of making it worse, in that assigning the computer an additional task, man-machine communication, may result in a requirement for even more instructions from the human.

There are four general approaches to the man-computer communication problem, each of which attempts to make the computer at least share the burden of communication:

1. Arbitrarily limit the flexibility and capability of the system

2. Reduce the number of instructions required by making each instruction more meaningful

3. Reduce the number of keyboard controls by making each control capable of performing many functions

4. Change the method of communication to one more familiar to or easier for the human

Existing navigation system controls generally represent some form of the first two approaches. The more limited systems offer only a few modes of operation, and communication with the system consists simply of selecting a particular mode or option. More complex systems attempt a compromise between system flexibility and control complexity by requiring the computer to interpret different sets of instructions in different ways. In essense, this is a "block programming" approach, as opposed to word-by-word input. System capability is still limited to however many "blocks" the computer is designed to accept. Additional disadvantages are that:

1. Inputs must be made in a precise order or format to be correctly interpreted, and instruction sets usually involve a code which must be either known or looked up.

2. How to operate the system is not intuitively obvious. The operator must learn how to use any particular system and, to be most effective, must understand how the system works.

The third approach, multifunction controls, is receiving most attention at present in that all three of the military services and virtually all major aerospace companies are developing or working with some kind of multifunction discrete control. Though the methods of achieving it differ, the concept is that each of a given number of controls, usually pushbuttons, can perform many different functions according to a defined logic sequence in an associated computer program. The computer drives the control head as well as the rest of the system, and the control head somehow displays the function of each control at any given time to the operator. The operator can call up any particular set of functions he desires, and the computer can request information by displaying a set of functional alternatives. Because a large number of functions can be selectively offered on relatively few controls, coded entries are unnecessary, and formatting requirements are minimal.

Human factors research on multifunction controls is lacking, partly because hardware suitable for research is lacking. Tests performed at Boeing (ref.27), AFFDL, and the Aerospace Medical Research Laboratory (AMRL) indicate that a given task takes longer to perform and requires more control operations with multifunction controls than with dedicated controls. It appears possible to offset this disadvantage in the design of the system by assigning functions to the computer wherever possible. Results of one analytical study (ref. 28) show that essentially equivalent workload levels between multifunction and conventional controls can thereby be achieved. No really significant test of the concept has been made to date.

Advantages of multifunction controls are (1) a dramatic reduction in panel space requirements, (2) optimum location for all controls involved, and (3) a means of giving the computer part of the task. Disadvantages are that (1) control functions must be performed via the computer, (2) all functions are not always available, and (3) a strong possibility for operator confusion appears to exist. This last possibility sorely needs research.

The fourth approach to man-computer interchange is to depart from the keyboard concept and use a different means of communication. A simple form of this approach is use of a joystick and cursor to designate navigation waypoints on a map display, rather than keying waypoint designations or geographic coordinates via pushbuttons. Cursor-laying is an effective means of target designation, but might be less effective for navigational waypoint designation. Use of a joystick and cursor for flight plan entry or modification would involve map slew and scale change operations not required for target designation, and perhaps more difficult and less accurate than corresponding keyboard operations.

A more dramatic departure from the keyboard for man-computer communication is computer voice recognition and synthesis (VRAS). Voice synthesis is a well established technology, but voice recognition is not. A VRAS system being developed by the Navy is capable of a recognition vocabulary of about 250 words. The system has the disadvantage of requiring not only carefully formatted, but also rather carefully spoken instructions, and a relatively simple operation can require a five- or six-word sentence, perhaps repeated. Even if the concept is acceptably developed, it is difficult to imagine its application in commercial airline cockpits. Its potential advantage to the Navy is that it would enable a single pilot to make weapons selections or whatever without having to release either the throttle or the stick. A similar system is being developed by the FAA to relieve air traffic controllers of time-consuming keypunch operations during peak traffic periods (ref 29).

4.3.4 WORKLOAD

The quantitative assessment of aircrew workload remains a problem, even though time-line analysis techniques have been shown to be remarkably accurate at predicting varying workload levels. The mental or cognitive aspect of workload is the elusive factor, though it has not been shown that the relatively gross methods of estimating cognitive workload used for time-line analysis are unacceptably inaccurate. McDonnell-Douglas in Long Beach is conducting a series of studies designed to yield baseline cognitive data on types, frequency, and difficulty level of tasks.

A "new" method of workload measurement which appears promising is interpretation of oculometer data, an approach currently being pursued by the Human Factors Branch at the NASA-Langley. Analysis of recent tests in an airline training simulator suggests that oculometer data might yield an index of cognitive workload, if correctly interpreted. It is clear that changes in scanning patterns, ranging from subtle to significant, occur in conjunction with changes in reported workload. The nature of this correlation is not clear, however, for several reasons, among which are: (1) both direct and inverse relationships between eye movements and workload level appear to exist, and (2) the oculometer data itself reveals that pilot reports of activity are often inaccurate. If the nature of this correlation could be established, the oculometer could provide not only a valuable record of visual activity, but also a continuous, quantitative indication of cognitive workload throughout any particular task. The primary developmental requirements for this application of the oculometer are: (1) a valid analysis technique, and (2) a corresponding computer program for appropriate data reduction.

Honeywell has developed a physiological technique of comparatively evaluating how much difference in operator effort and attention is required for two or more similar tasks, i.e., comparative "physical cost." The technique involves measurement of EKG, muscle activity, and respiration rate, but these data are said to be treated differently than they would be for classical stress assessment. If the technique does, as claimed, measure the compensation provided by the test subject in an experimental task, it could be very valuable. Task performance measures in comparative experimental tests are often inconclusive simply because the test subject works harder in one case than in the other to achieve a personal standard of performance. Performance differences do not appear until the subject is physically unable to compensate for the greater difficulty of one of the two tasks. Honeywell's technique is said to be sufficiently sensitive to discriminate between two similar formats of the same display.

4.3.5 COLOR DISPLAYS

Color offers two advantages in displays: operator appeal and a means of information coding. The utility of operator appeal is difficult to quantify, and thus also difficult to justify economically. The utility of color as a coding dimension can be quantified, and test results show generally that the utility of color is highly dependent on the nature of the task (ref. 30). Color is not significantly more advantageous than achromatic codes, such as shapes, symbols, and alphanumerics. It is obviously valuable as another coding method where other achromatic codes are already "used up." When applied as one of several codes, however, color can actually interfere with extraction of information from a display.

At present there does not appear to be a demanding application for color in electronic displays for commercial aircraft. Color is already used in the cockpit as a background code for caution, warning, and equipment status, and its use is perhaps best confined to those applications. It can be remarkably effective when generated artificially and used to enhance contrast for sensor displays (ref. 15). If an imaging sensor is tested as a low-visibility landing display, this application of color should be explored.

4.3.6 IMAGE QUALITY

The Office of Naval Research and the Air Force Aerospace Medical Research Laboratories both support R&D in the area of display image quality assessment, and AMRL does some of this work internally. The goal of the research is, generally, to achieve a quantitative description of image quality and thus an analytical tool for the design of imaging systems and prediction of operator performance. Most of this work is aimed at improving sensor-aided target acquisition, but one program at Virginia Polytechnic Institute will assess the effect of a number of display variables on the interpretability of raster-generated alphanumerics. None of this work appears of immediate use to TCV. A research tool at VPI which might be of interest is the "eye tracker," a high-frequency, continuous output oculometer which can indicate not only where the eye is directed, but also where it is focused. In order for the machine to hold track, however, the eye must remain within 1 cc volume.

4.3.7 FLAT-PANEL ELECTRONIC DISPLAYS

The cathode-ray tube displays in the TCV airplane represent a display system which, though still accurately described as "advanced," is a mature and well-developed technology. Although CRT displays are not yet common as other than weather radar displays in commercial transport airplanes, they are well represented in military aircraft, both as dynamic cockpit displays in attack airplanes such as the F-14 and A-6, and as other crew station displays in larger aircraft such as the P3 (ASW), B-1, and E-3A (AWACS). In these applications, CRT's have proven to be safe, reliable, and effective displays. Many current CRT applications employ an analog drive, but the CRT is eminently applicable to a digital drive, and appears at present most likely to be the basic display device for future digital avionics systems, such as the Air Force DAIS and Navy AIMIS/AIDS.

The CRT is being challenged for this role by several much newer technologies, all of which may be generally described as "solid-state" or "flat-panel" electronic displays. Within this family are light-emitting diodes (LED's), liquid-crystal displays (LCD's), plasma or gas-discharge (GD) displays, and light-emitting films (LEF's), basically an advanced form of the older electroluminescence (EL) technology. All these devices are inherently digital, i.e., they are fabricated in element arrays and must be addressed via an x-y matrix excitation. Herein lies a weakness, rather than a strength, however. Large arrays, such as the 512 x 512 normally used for TV, require the fabrication and packaging of more than 1000 individual leads. In general, an array of m times n elements requires m + n connections and line drivers. There are exceptions to this requirement, and also methods of reducing the number of connections to less than m + n, but only by increasing the complexity and cost of the display driving circuitry. By contrast, a CRT may be driven via a half-dozen or so connections at the most, regardless of the number of "elements" in the "array."

The major advantages of flat panel over CRT displays are in space, weight, and power requirements. Virtually all these displays can be packaged so that their depth, including driving electronics, is in the range of 6 to 10 cm. Power requirements are not easily generalized, but none begins to approach the power requirements of CRT's. The gas-discharge displays require the highest voltage, 200 to 300 V, but consume relatively little power. LED's operate at logic-level voltage (5 V), but can require up to 70 mA each for maximum brightness. LCD's also operate at low voltage (15 V) and require only microamps of current.

All these solid-state displays are potentially capable of generating different colors, but none has as yet a "color TV" capability. In general, different colors are achieved by changing the natural display color via deposited phosphors, but pure colors are difficult to achieve in this way, and display brightness inevitably suffers. Brightness, however, is primarily a means of achieving contrast in CRT's, and most solid-state displays have inherent high contrast. In the passive, reflective LCD, contrast remains constant as ambient light increases, and the display literally cannot be washed out by high levels of incident light. In the dark, an auxiliary light source must be supplied. In addition, LCD's suffer from relatively slow response time and have limited viewing angles.

Beyond these technologies are still others, such as electrochromics, which operates via electrically induced chemical change, and electrophoretics, in which suspended pigmented particles are electronically arranged and rearranged to make up the display. At present, these are laboratory curiosities, much as are exotic devices such as laser-generated displays, and even the TV-quality plasma and liquid-crystal displays recently demonstrated. LED, plasma, and liquid-crystal displays for alphanumerics and simple graphics have already arrived, not only on watches and calculators, but also as data displays and multifunction switch legend displays in advanced military aircraft designs. Within the foreseeable future, the CRT will almost certainly have a viable contender for dynamic, electronic cockpit displays in the form of a low-volume, low-power, solid-state device.

The CRT displays of the TCV B-737 offer the same or greater flexibility in symbol generation as any of these devices. Developments in this area should continue to be monitored, because significant improvements in solid-state display technology could accelerate the practicality of airline use of computer-generated, dynamic displays. Unless a specific requirement for a new display surface is identified in the TCV B-737, however, TCV evaluation of these devices does not appear warranted.

5.0 RECOMMENDATIONS

5.1 GENERAL

The following recommendations are made on the basis of both survey and analysis information, and in consideration of the goals and resources of the TCV program. The recommendations are presented in decreasing order of priority, with consideration given also to economic and feasibility factors. Evaluation of the tactile display (sec. 5.6), for example, is not of "higher priority" than the succeeding recommendations, but rather appears to be something which could be begun almost immediately because the basic developmental work has already been done. Similarly, the VAM evaluation (sec. 5.5) should be performed, if at all, while outside support is still available. All recommendations are oriented to the TCV Crew Integration program. Recommendations 5.2 through 5.4 represent what is perceived as crucial for the success of the program: (a) that TCV must document and communicate all activity relevant to research on and evaluation of advanced transport operations; (b) that primary effort be devoted to furthering the control/display research and development already begun in the program; (c) that quantitative and comparative evaluation of these advanced flight deck concepts be accomplished.

5.2 DOCUMENTATION OF ACTIVITY

- Identify, document, and distribute results of simulator and flight tests and human factors problems encountered in test and evaluation operations.

The TCV program is uniquely capable of addressing problems foreseen in the real world of terminal-area operations. It is also uniquely capable of identifying unforeseen difficulties in this context, as they arise in the TCV B-737 operations. It is vital that this type of information be distributed to others in the field who lack the resources to discover or define such problems themselves, but who can contribute to the solutions of problems, once identified. An active program should be established for rapid documentation and dissemination of analysis, simulator, and flight test results, whether positive or negative, conclusive or inconclusive. Similarly, an aggressive program for collecting outside research and development results and ensuring their dissemination within the TCV program is necessary. Maintenance and encouragement of continuous technical interchange with others in the field is essential to accomplishing program objectives.

Besides disseminating and publicizing results of TCV activity, consistent documentation would promote a coherent systems approach to analysis of control/display tasks. At this juncture in flight deck development, "breakthroughs" or even significant advances are likely only via exploitation of new approaches to the division of work and responsibility between the man and the machine. Progressively learning to apply the tremendous computing and processing capability now becoming available holds the greatest promise for achieving significant and lasting advances in commercial aviation. Without a record of attempted improvements, including both rationale for tests and analyses of success or failure, the significance of either any particular idea or results from any particular evaluation is difficult to relate to long-range objectives. Such a record would not only forestall repetitive experimental efforts, but also would suggest, justify, and provide guidelines for new efforts.

Because many different individuals and organizations support and contribute to the TCV program, such a documentation effort must be centrally administered and kept simple. With respect to administration, it is recommended that:

1. A short flight/test summary report form be devised in an annotated outline format

2. A single individual be assigned to prepare and distribute the reports on an aperiodic "event" basis

3. Only individual flight and simulator tests, and significant experimental and analytical findings, both positive and negative, be summarized on each report (The medium must not become a periodic "progress report".)

4. To expedite circulation, minimum formal approval be required prior to report distribution (A suitable purpose statement and disclaimer should be included on each report.)

5. Each report include a page or section encouraging readers to respond with comments, questions, and accounts of related activity

6. A distribution list of appropriate organizations be prepared and maintained by the individual charged with preparation of the reports

5.3 CONTROL/DISPLAY CONCEPT DEVELOPMENT

- Focus primary effort on analyzing and developing control/display concepts, particularly those currently implmented in the TCV B-737, which are designed either to relieve the pilot of inner-loop control tasks or to simplify outer-loop tasks, and thereby facilitate his functioning as system manager.

Examples of such currently implemented concepts and corresponding necessary developmental work are:

Concept	Development required
Velocity vector control wheel steering (CWS)	Evolve display and control provisions to permit precise achievement of desired velocity vector.
Automatic guidance and control system (AGCS) control panel	Make display and control changes to improve control panel interpretability and operability.
Thrust management system	Devise a full time automatic (or semiautomatic) thrust management system compatible with manual and automatic flight modes.

Two-, three-, and four-dimensional operations	Identify manual techniques, control laws, and display provisions for smooth and efficient path capture and following. Identify information and situation display requirements for three- and four-dimensional operation.

This work comprises several levels of machine assistance to the pilot, and is fundamental to both validating the currently implemented concepts and to progressing beyond these. Concepts other than the foregoing might be developed, but none has been proposed which appears to offer the degree of pilot unburdening possible via velocity CWS and automatic path guidance modes. Experimental development of these concepts is essential both for accurate assessment of potential navigation and guidance benefits, and for evaluation of secondary control/display concepts which inevitably interact with these via demands on the aircrew's time and attention. Few, if any, other organizations have the means to develop, test, and evaluate such concepts realistically. Some aspects of this research program might be contracted to other agencies, but the bulk of the work is necessarily a TCV B-737 effort.

The experimental development of primary AFD control and display concepts should be of first priority. Until these primary capabilities are refined to optimum levels of operational utility and efficiency, unnecessary effort and attention will be required of the AFD pilots to perform primary control tasks, and these additional physical and mental requirements will inevitably affect negatively other test and evaluation functions performed. Any other flight deck evaluations that are performed prior to optimizing AFD controls and displays should address relative, rather than absolute, crew performance. Care should be taken that all comparable aspects of the evaluation are equally affected by the control/display implementation.

The continued development and refinement of control and display concepts incorporated in the TCV B-737 is proper, highly desirable research and development activity, and is not to be approached or regarded as avionics hardware development work. No other research vehicle has or has had the capability to conduct actual flight operations using a similar complement of advanced controls and displays. Unforeseen aircrew interface problems experienced in the TCV B-737 operations are important research findings. Such problems should be documented and their basis and possible solutions pursued as primary program research work, as recommended in section 5.2

5.4 ADVANCED CONTROL/DISPLAY SYSTEM PERFORMANCE ASSESSMENT

- Quantitatively assess pilot performance for selected system tasks and aircraft maneuvers using advanced displays and controls.

Quantitative performance improvement data for any advanced control and display concept is a necessity if recommendations for commercial implementation of such concepts are to be made. Baseline advanced electronic display system (ADEDS) and CWS performance data is similarly necessary for comparative evaluation of control and display concepts other than those currently under development.

The traditionally slow process of new control and display implementation in transport aircraft can be partly attributed to a lack of operationally derived comparative system performance data. Quantitative performance data is normally either unavailable or incomplete for new developments. What little data is available for existing conventional implementations is usually deficient, thus making performance comparisons virtually impossible. The cost to transport operators of implementing a change in the flight deck is easily quantified, however, and this negative factor usually prevails, perhaps justifiably, when weighed against qualitative advantages and theoretical estimates of improved performance.

Again, TCV is uniquely capable of contributing in this area. The flexibility and versatility of the TCV B-737 make TCV potentially capable of providing both a performance data base for conventional flight deck configurations and comparative performance data for new flight deck concepts.The systematic accumulation of such data is appropriate to TCV goals, and in addition, would be of immediate utility to the entire transport aircraft community, operators, manufacturers, and researchers. Such a program of continuous and progressive concept assessment would provide a focal point for all flight deck R&D, would speed the implementation of worthwhile developments, and would provide tangible evidence of the shortcomings of others.

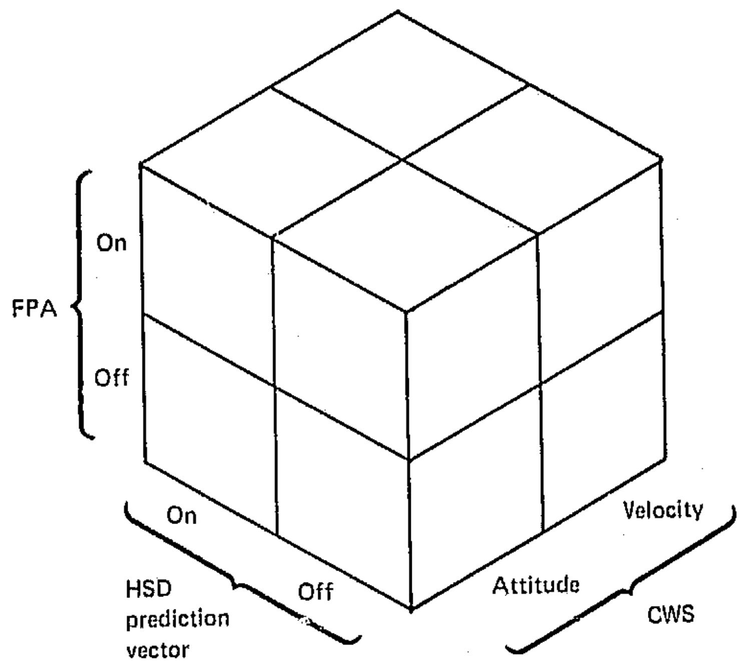
As the first step toward quantitative performance assessment, routine two-man operations from the AFD, as nearly full-time as possible, should be established as the normal operational mode for all experimental flights. The utility of a secondary monitoring and discrete control task in the AFD should be explored. The purpose of such a task would be both to simulate subsystem control and display functions and to provide a measure of attention given to such secondary functions during flight. The secondary task should be designed on the basis of time-line data and validated by comparative oculometer tests, probably best performed in the simulator.

The nature of the concepts to be evaluated, appropriate experimental tasks, and the parameters to be measured must be studied specifically, but some experimental requirements may be inferred. Due to the time and expense involved in flight tests, the number of experimental tasks in any particular test must be limited to two or three. For the same reasons, classic experimental techniques such as counterbalancing variables, use of many experimental subjects, and training subjects to asymptotic performance levels, cannot be used. To provide a common base for all test data, basic parameters such as flight path deviation and control activity should be recorded for all tests, in addition to other parameters specifically relevant to any particular test.

Initial tests should be designed to assess the contribution of individual aspects of the AFD control/display system, and should be kept as simple as possible. For example, comparative assessment of performance on a standard approach might be made for:

- Display versus no display of FPA and potential FPA
- Display versus no display of horizontal situation display (HSD) path prediction vector
- Velocity CWS versus attitude CWS

Each of these comparisons could be made in a three-variable test, and possible interactions between variables could be assessed using a test matrix such as that shown below.



For these and other tests, control modes and display content must be made harmonious relative to the task and concept being tested. As data are accumulated, more complex assessments may be made, such as system path following performance on curved or segmented approaches. In such tests, it may be impractical or impossible to obtain comparative data using more conventional instrumentation, but a quantitative assessment of advanced system performance for such tasks would be valuable in itself.

An obvious requirement for this work is that the concepts tested be sufficiently well developed to be fairly evaluated, hence the priority of the preceding recommendation, "Control/Display Concept Development." Because the number of experimental subjects and tests must be minimized, for reasons of time and cost feasibility, care must be taken to avoid biasing results with inadequately developed or implemented concepts. Similarly, the possibility of purely fortuitous superior performance will be increased in such limited tests. Both test design and data analysis must be done especially carefully with cognizance of these possibilities.

5.5 VAM EVALUATION AND HUD TEST PROGRAM

- Evaluate the visual approach monitor for curved and segmented approaches. Define a simulation test program for test of a head-up display for both VFR and IFR approach and landing.

Cooperation and support from both Sundstrand Corporation and AFFDL has been indicated for the VAM evaluation. Simultaneous evaluation of a PAFAM unit might be done in the rear cockpit, if one could be obtained and if interface problems were not prohibitive. Results of McDonnell-Douglas' PAFAM evaluation should be examined before proceeding with tests on the TCV B-737, however.

Use of a HUD as a landing aid is an issue which has all the earmarks of developing into a CDTI-like problem in which great heat but little light is generated. A rigorous test of the HUD for commercial operations will be complicated and expensive, requiring a visual simulator in which varying conditions of visibility can be represented, and closed-loop approach and landing performed. The first step toward such an evaluation should be a role-definition study and subsequent delineation of test requirements.

A large amount of qualitative operational information is available from the military and perhaps from British and European airlines which use a HUD. Some regional U.S. airlines have purchased VAM's, and McDonnell-Douglas is evidently flight testing a HUD on a DC-10. These sources might contribute data and perhaps otherwise support or take part in the program. Operational information should be compiled and analyzed for indications of relevant tests. Manufacturers of head-up displays and of military aircraft should also be consulted for information and possible participation.

5.6 TACTILE DISPLAY EVALUATION

- Evaluate the tactile display concept developed at Ohio State University for presentation of angle-of-attack and flare command. Investigate its utility for presentation of other parameters as appears desirable and feasible.

This device has been shown to improve significantly the approach and landing performance of student pilots. Experienced pilots have made under-the-hood landings using the display, but no significant test or evaluation by experienced pilots has been made. It is possible that an experienced transport pilot might find a qualitative indication of angle-of-attack (AOA) command uniquely useful. Experienced pilots probably would not "obey" the display, but might use it to either achieve or maintain a particular AOA, and might also find it helpful for flaring the airplane. Such an evaluation appears particularly suitable for the TCV B-737 where the qualitative AOA and flare indications on the EADI could be compared with the tactile indications.

Results of this evaluation would have significance beyond the specific utility of the tactile display itself. Use of AOA as a primary flight parameter in transport aircraft is an oddly controversial problem. There is nearly universal agreement on the theoretical utility of AOA to the pilot, but also universal reluctance to display AOA on the flight deck. AOA is supplied as an input to transport autothrottle systems, but not to transport pilots. Reasons for this lie in unknowns or uncertainties associated with accurate presentation of the information, training of pilots in its use, and procedural difficulties stemming from large aircraft operations in the presence of windshears and turbulence. Because the tactile display provides a very simple presentation and requires minimal pilot training, it offers a means of backing into the problem. The utility of a visual raw-data display, or visual versus tactile command could be assessed. Whatever results were obtained, the evaluation could provide a basis for a more comprehensive and certainly a valuable investigation of all aspects of AOA as a primary flight display.

In addition to the AOA application, the tactile display may be useful for qualitative presentation of virtually any single-dimensional parameter, thus unburdening the visual channel. The concept might be applied as (a) throttle command based on time error, or (b) direct-lift command based on flight path deviation. A two-dimensional device is under development. If the single-channel device is evaluated favorably, the two-channel version might then be tested, perhaps as a "head-up" indication and/or command of vertical and lateral flight path deviations.

5.7 COCKPIT DISPLAYED TRAFFIC INFORMATION

- Define a simulation test program for CDTI functions. Test the display for use in monitoring simultaneous independent approaches to close parallel runways. Continue with other tests which appear desirable and are feasible.

The Boeing-FAA study of CDTI role concept formulation (ref. 25) has been completed, and the document includes recommendations for experimental tests. It is reasonable to assume that the FAA will encourage at least limited testing of selected roles. The NASA-Ames and the NASA-Langley are logical choices for performance of some of these tests.

Although it would be possible and in some ways advantageous to implement a CDTI presentation in the research cockpit, simulator testing would be more cost effective. Moreover, testing should focus not only on the possible advantages of CDTI, but also on its potential weaknesses. Test subjects must be well trained in use of an HSD/electronic horizontal situation indicator (EHSI) to avoid contaminating results with improvements in performance that are due to learning and unrelated to the method of presentation of traffic information. Both visual and nonvisual simulators will be required to investigate differing use of the display in VFR and IFR conditions. A set of requirements for visual simulation tests should be established, and the capabilities of the NASA-Langley in this respect should be evaluated.

The most readily available sources of support for the study are those which were involved in preliminary testing: Tufts University, MIT, and the NASA-Ames. AFFDL's Terminal Area Control Office and Randolf AFB's Instrument Flight Center might lend support. The University of Illinois and major aircraft manufacturers having suitable simulators are other possible sources. Limitations of these resources are most likely to be in their capabilities to realistically simulate traffic and in the availability of pilot subjects experienced in the use of an HSD/EHSI.

5.8 KEYBOARD RECONFIGURATION

- Evaluate the potential of multifunction switching at the navigation control and display unit (NCDU) for crew-computer communication.

At present, the logical application for multifunction switching, if one exists, is at the NCDU, the most complicated control panel on the flight deck, and a source of significant workload. An evaluation of multifunction switching in the NCDU would indicate its potential for reducing both keyboard complexity and aircrew workload. In addition, valuable information on future crew-computer communication tasks might be gained.

The multifunction controls themselves will operate in whatever manner they are programmed; hence, the functional design is critical to evaluation of the concept. Maximum advantage of interface and processor logic must be taken to ensure both natural progression of modes and functions, and minimum operator input requirements.

It is recommended that the evaluation be performed in the simulator, rather than in the airplane, for two reasons: (1) currently available multilegend switches have low display brightness and are adversely affected by vibration, and (2) test panel interface requirements would be simpler in the simulator. Favorable results from the simulator test might encourage development of flight-suitable hardware for a subsequent flight test of the concept.

5.9 WORKLOAD EVALUATION AND VALIDATION

- Continue development of the oculometer as an experimental tool.
- Validate the time-line analysis program (TLA-2).
- Evaluate the "physical cost" comparative workload evaluation technique for possible use in future TCV operations.

The oculometer can provide valuable experimental data concerning the amount of visual attention–frequency and dwell time –devoted to various displays and display areas. This type of visual data is otherwise unobtainable, particularly since experimental subjects are often unaware of, and thus cannot report, significant portions of their visual activity. The work currently in progress at the NASA-Langley to develop (1) optimum cockpit installations for the oculometer, and (2) an effective, flexible data reduction program, should be continued on a high-priority basis.

In addition to providing a record of visual activity, the oculometer offers a potential means of cognitive workload measurement, continuously determined, for any particular task. Use of the oculometer in this application will require experimental development and validation of an effective data analysis technique, as well as an appropriate data reduction program. Candidate analytical techniques should be based on known physiological and psychological aspects of vision, perception, and cognition. Technical support from specialists in these areas is recommended.

Validation of the TLA-2 workload program should proceed as planned. The purpose of this program is to estimate and predict absolute workload levels; hence, the two techniques are not redundant. McDonnell-Douglas has a comparable workload program and is pursuing a more precise definition of cognitive workload. Progress of this endeavor is proprietary, but such information may be made available to the TCV program if requested.

As discussed in the survey and analysis section (4.3.4), the "physical cost" comparative workload technique could be uniquely valuable in the evaluation of rival configurations or formats which are not sufficiently different to produce differences in measured performance. This technique might also be useful for overall evaluation of very complex tasks as well as tasks for which an appropriate performance measure is not easily identified. For example, it might offer a means of quantifying the "operator appeal" factor in color displays. A first step must be tests of the technique itself to establish its sensitivity and utility for airborne as well as simulator tests. AFFDL has indicated interest in this work, and might lend support for further development and evaluation of the technique.

5.10 STEREO DISPLAY EVALUATION

- Continue development of the stereo display concept. Compare the potential of two- versus three-dimensional displays for information transfer.

The stereo display concept can apply to both computer-generated and imaging sensor displays. Its potential for either application should be assessed via comparative evaluation of information content and pilot-subject performance.

The 3-D display development currently sponsored by TCV at McDonnell-Douglas should be continued with the objective of performing a 3-D versus 2-D evaluation of the concept itself, apart from associated airborne sensor systems. If results of the evaluation indicate a significant advantage for 3-D displays, either further development of the McDonnell-Douglas approach or test of the Honeywell PLZT-goggles system should be pursued. Neither of the two approaches appears amenable to realistic closed-loop simulator testing. Thus, the advantage of the concept should be definitely established before embarking upon installation and test of such a system on the airplane.

A 3-D display system, similar to Honeywell's, was built by RCA for Johnson Space Center for possible use on the Space Shuttle. This system is not currently in use at Johnson Space Center, and might be available to TCV.

5.11 IMAGING SENSOR EVALUATION

- Investigate the feasibility of performing a ground-based evaluation of imaging-sensors in low visibility, including the potential of image enhancement and stereo display techniques.

Despite the objections to an imaging sensor landing display, the idea of showing the pilot an actual view of the ground remains attractive. Results of the AFFDL evaluation of the Texas Instruments Ka-band radar ILM will be published soon. The device itself is available, and Texas Instruments might support its consignment to the TCV program.

The display device itself, as well as the rest of the system, would be required, because the presentation is not TV compatible. Another sensor system possibly available to the program is the Hughes FLIR, described in section 4.2.3.

Neither of these devices is recommended for evaluation on the TCV B-737 because of the hazard involved with making experimental approaches in actual low visibility. More relevant tests of each might be made in some other vehicle, such as a truck, for purposes of low-visibility turnoff and taxi assessment. Testing both at the same time would be particularly revealing.

Dual-sensor integration and generation of artificial color for image enhancement should be pursued via a low-level study effort. Westinghouse, Cerberonics, and others in the target acquisition display field might provide support.

6.0 SYNOPSIS OF RECOMMENDATIONS

6.1 PRIMARY PROGRAM EFFORT

The following three recommendations are seen as fundamental to the TCV program and as critical to its continuation and success.

6.1.1 DOCUMENTATION OF ACTIVITY

The TCV program has, in the TCV B-737, a unique capability for discovering unforeseen operational problems, as well as for addressing such problems in the real-world environment. It is vital that TCV experience and test results be disseminated to others in the field. An aggressive technical interchange effort will benefit TCV as well as others. To promote this interchange the TCV program should identify, document, and distribute results of simulator and flight tests and human factors problems encountered in its test and evaluation operations.

6.1.2 CONTROL/DISPLAY CONCEPT DEVELOPMENT

The guidance, control, and display concepts currently implemented in the TCV B-737 must be improved via experimental test and evaluation toward an optimum level of harmony and operational utility. This work is necessary not only to eventually achieve reliable performance measures for the advanced concepts themselves, but also to ensure that concurrent and future studies of other flight deck concepts are not biased by unnecessarily difficult primary flight control tasks. This concept development is fundamental to successful TCV B-737 operations, and is in no sense commercial avionics system development.

6.1.3 ADVANCED CONTROL/DISPLAY SYSTEM PERFORMANCE ASSESSMENT

Pursuit of the basic objective of the TCV program--to develop, evaluate, and demonstrate improved systems and procedures--requires a systematic and quantitative assessment of aircrew performance using new procedures and advanced controls and displays. Again, TCV is uniquely capable of obtaining reliable system performance improvement data for such new concepts. Such data can provide the only realistic means of trading system cost against system performance in the real-world environment.

6.2 SECONDARY CONCEPT EVALUATIONS

Each of the following represents a relatively well-developed candidate concept for TCV flight test or simulator evaluation.

6.2.1 VAM EVALUATION

A systematic evaluation of the role and utility of the Visual Approach Monitor for commercial terminal area operations would be valuable both in itself and as data relevant to the general head-up display question. The TCV B-737 FFD is configured for the VAM, and support is available from Sunstrand Corp. and perhaps from AFFDL also.

6.2.2 TACTILE DISPLAY EVALUATION

A tactile display concept, developed at Ohio State University, has been shown to improve significantly the landing performance of student pilots when used to present angle-of-attack command. The device is potentially capable of presenting any single-dimensional parameter, and thus of unburdening the visual channel by one item. Angle of attack is not currently displayed in transport cockpits. Test of a "conditioned" and easily interpreted angle-of-attack tactile signal would be relevant to both the tactile display evaluation and the larger general question of angle-of-attack display on the flight deck.

6.2.3 KEYBOARD RECONFIGURATION

Hardware, software, and experience exist for performing a simulator evaluation of multifunction controls as a means of both simplifying the navigation system control head and improving man-computer communication. A multifunction control head fabricated for this evaluation could then be reprogrammed for other applications, and would provide a useful optional capability in the simulator.

6.2.4 WORKLOAD EVALUATION AND VALIDATION

The TLA-2 workload analysis program should be validated by comparing predicted and actual time requirements for significant flight deck evolutions in both the airplane (FFD and AFD) and the simulator. Such validation is necessary if the program is to provide reliable and therefore useful data in the future.

Evaluate the comparative "physical cost" workload assessment technique. Determine its sensitivity and potential for use in TCV experimental operations.

6.2.5 STEREO DISPLAY EVALUATION

The stereo display concept appears to offer a needed third dimension in cockpit displays. Fundamental tests of 3-D versus 2-D displays should be conducted to determine how much and what kind of additional visual information, if any, can be extracted from a stereo display. The possibility of future cockpit tests should be considered when establishing display parameters and experimental tasks for these tests.

6.3 STUDY AND ANALYTICAL EFFORTS

These recommendations require study and analysis before actual flight or simulator evaluation is undertaken.

6.3.1 HUD TEST PROGRAM

The utility of a head-up display for transport aircraft is a question for which there is little or no relevant experimental or empirical data. Actual test of the head-up display concept for approach and landing use is needed, but such testing must be carefully planned. Information relevant to the HUD in the commercial role should be compiled and analyzed with the aim of eventually defining HUD test requirements.

6.3.2 CDTI WORK

The cockpit displayed traffic information concept has progressed beyond preliminary test and evaluation, and now is ready for more involved and complex testing. Simulation test requirements should be defined, and the capabilities of available simulators evaluated with respect to such requirements.

6.3.3 OCULOMETER DEVELOPMENT

The oculometer is potentially useful as an experimental tool which can provide (a) a record of visual activity, (b) an indication of cause and effect relationships, and (c) a measure of cognitive workload. Its application for all three purposes requires development of suitable data reduction methods. For workload measurement, an analysis technique must be developed as well.

6.3.4 IMAGING SENSOR EVALUATION

A short feasibility study should be conducted prior to embarking on this evaluation. The object of the study should be to determine equipment availability, manpower, time and cost requirements, locale, method of approach, and provisions for image enhancement, if any. The object of the evaluation itself should be to establish the capability of imaging sensors to penetrate rain, snow, fog, and haze.

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